



Exposure Assessment to Whole Body Vibration (WBV) at Launch Loads

VATF Facility



- The NASA Johnson Space Center (JSC) Vibration and Acoustic Test Facility (VATF) is operated by the Structural Engineering Division within the JSC Engineering Directorate.
- The VATF has been operational since 1965, supporting Apollo, Skylab, Shuttle, International Space Station, Orion, and others.
- The VATF planned to expand its capability to include human-rated test services to safely support human-in-the-loop engineering evaluation of hardware and equipment in a vibration environment.

Note: Human vibration testing was performed at the VATF in support of Apollo



Testing



- These laboratories provides **hardware** testing for the following:
 - Development/Evaluation
 - Qualification (design verification) Certification
 - Acceptance (workmanship) Certification
 - Operational or Flight Anomaly Investigations
- The facility can perform a wide range of tests needed to evaluate all aspects of structural dynamics including the following:
 - Vibration
 - Vibro-acoustics
 - Modal Characteristics
 - Sound Transmission Loss
 - Shock

Capability

- Vibration Input
 - x, y, or z load direction
 - High-force vibration (random, sinusoidal, & shock)
 - Horizontal & vertical test beds
- Digital vibration control system
 - 32 channels
 - Multi-shaker drive capable - up to 4 independent shakers
- Digital data acquisition
 - 288 ICP channels
 - Frequency range 5-10,000 Hz
 - Up to 60 minutes
 - Data sampling rate up to 100,000 samples/sec per channel
- Other
 - High speed camera
 - Photogrammetry setups



Crew Quarters Modal Testing



General Vibration Laboratory

Change in Rocket Fuel Changes Thrust Oscillation Profile



- Mercury, Gemini, & Apollo programs used liquid fuel
 - Subject to pogo, a longitudinal oscillation or vibration that can occur when a surge in engine pressure increases back pressure against the fuel coming into the engine, reducing engine pressure, causing more fuel to come in and increasing engine pressure again. If the cycle happens to match a resonance frequency, it can harm the vehicle.
 - Vibration analysis is used to stay away from resonance frequencies, plus damping mechanisms are used (e.g. damping propellant lines).
- New rocket under development, Ares 1, to use solid fuel
 - The solid fuel burns outward from the center of the cylinder, and when gone leaves a hollow metal tube that can behave like an organ pipe. When the wavelength of the vibrations equals the length of the pipe, the vibrations are amplified.
 - Vibration analysis is used to stay away from resonance frequencies, plus active and passive damping mechanisms are used (e.g. mass absorbers).

Change in Launch Position of Human Crew



Apollo Atop
Saturn V:
Liquid Fuel

4/17/2014



Space Shuttle Attached to
External Tank:
Liquid Fuel for Main Engines,
Solid Fuel for Boosters

P. Stanch



Orion Atop Ares 1:
Solid Fuel

6

Human Performance Concerns



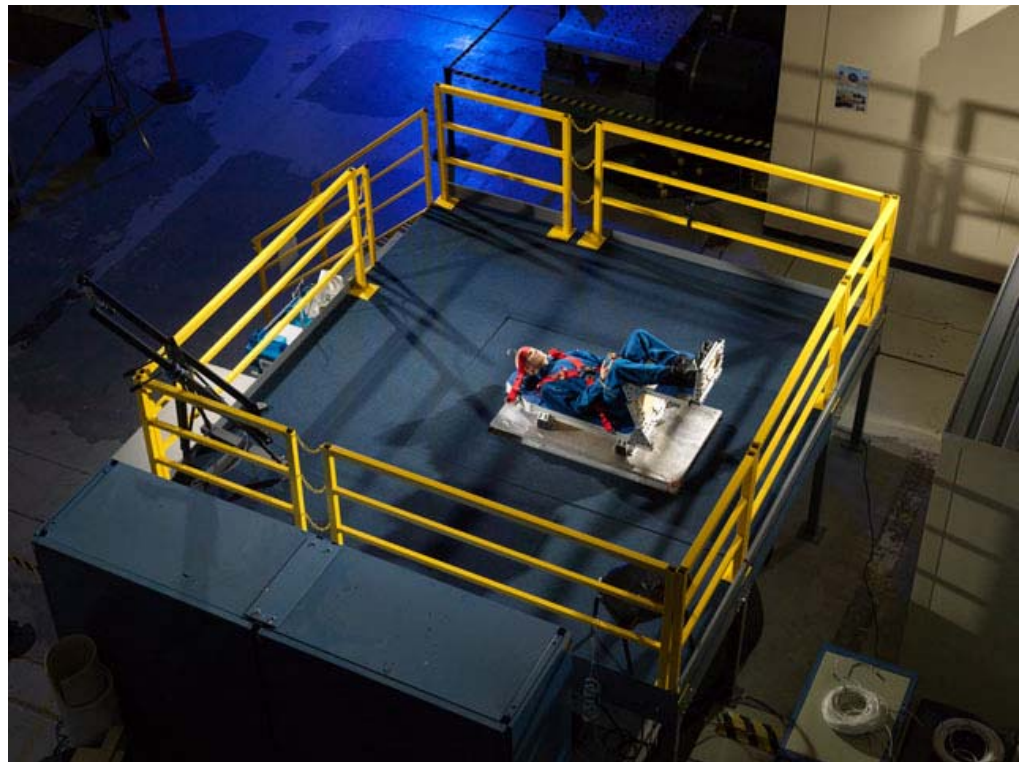
- Ares 1 design needed to limit vibration to levels safe enough to prevent injury or illness, but also low enough to permit the crew to maintain:
 - Situational awareness
 - Operational capability during launch
 - Ability to monitor vehicle health and status
 - Ability to perform mission-critical off-nominal operations
- Desire for a **Human-rated Vibration Test Bed (HRVTB)**:
 - **Don't** want to know how much the human can tolerate
 - Vehicle design should limit exposure
 - **Do** want to know how to configure the controls & displays to maximize crew performance during launch
 - Can't totally eliminate exposure

Shaker System



DS-4400VH-12 Electrodynamic
Vibration System

HRVTB – Final Configuration



Abort Systems

Besides the Jaguar Vibration Control System, there are several abort systems:

- Variac Voltage Limiter Box (fail safe)
- Four manual abort switches
 - Three hand-held momentary switches for Test Director, Amplifier Operator, and Medical Officer or Principal Investigator
 - One “dead-man” switch for Test Subject
 - All circuitry is two fault tolerant
- Independent abort sensor triggered by vibration threshold limits
 - Limits are programmed into the real-time Human Vibration Monitor
 - Vibration/acoustic monitor (Quest Technology VI-410)



Seat-pad
accelerometer



VI-410

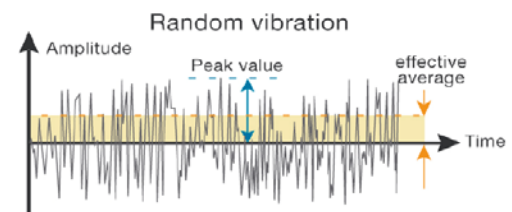
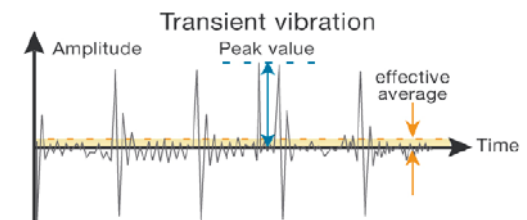
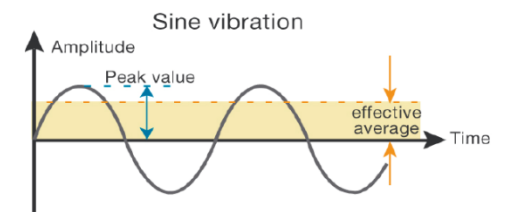
Questions to Occupational Health Branch



- What is the acceptable exposure limit?
 - **Default** profile considered acceptable
 - Protocols exceeding limit would need further IRB evaluation
- How is cumulative exposure calculated?
 - Can the same test subject be used in multiple runs on the same day?

Vibration Exposure

- Vibration is a time-varying oscillatory motion of a mechanical or biological system about an equilibrium position.
- Similar to Sound, Vibration measurement consists of two main components, Amplitude and Frequency.
 - However, while what we perceive as Sound manifests from a variation in Pressure, (hence SPL), Vibration is a physical variation in the location of matter.
- This cyclical physical movement can be described by its Acceleration (m/s^2) and Frequency (Hz).



Vibration Exposure



- For purposes of exposure assessment:
 - Frequency values in 1/3 octave bands are integrated for frequency weighted (w) acceleration value.
 - Acceleration values (a) are integrated for a resultant rms value of vibration level (A).

- $A_w = \sqrt{\sum_{n=1}^i (w_i a_i)^2}$

- Vectors for the 3 ordinal directions are summed for an overall weighted total rms acceleration equation

- $A_{wt} = \sqrt{(A_{wx}^2 + A_{wy}^2 + A_{wz}^2)}$

OELs for Whole Body Vibration (WBV)



- ISO 2631-1 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration
 - Does not give a limit, rather
 - Vibration evaluation and instrumentation
 - Frequency weighting
 - Applicability of evaluation method
 - For WBV of seated persons, ISO recommends additional multiplier for x & y accelerations to calculate total dose:

$$A_{wt} = \sqrt{((1.4A)_{wx}^2 + (1.4A)_{wy}^2 + (A)_{wz}^2)}$$

- To calculate the 8hr weighted average sum: $A_{was,8} = \sqrt{\frac{\sum A_{wt}^2 T_i}{8}}$

- Section 7 Health 7.1 Application

"This clause concerns the effects of periodic, random and transient vibration on the health of persons in normal health exposed to whole-body vibration during travel, at work and during leisure activities. It applies primarily to seated persons, since the effects of vibration on the health of persons standing, reclining, or recumbent are not known."

OELs for Whole Body Vibration (WBV)



- OSHA – does not have a WBV standard
- EU WBV standard
 - Daily Exposure Limit Value 8hr – 1.15 m/s²
 - Daily Exposure Action Level 8hr – 0.50 m/s²
 - Calculated as the highest A (rms) value of the frequency-weighted accelerations, determined on three orthogonal axes
 - Assumes seated or standing worker
- ACGIH TLV values are frequency dependent
 - Thrust oscillation profile uses 10-16 Hz
 - TLV A_x or A_y 8hr – 1.12-1.80 m/s²
 - TLV limits in the z direction (foot-to-head) are higher than the TLV limits for the x direction (back-to-chest) & the y direction (side-to-side).
 - Uses same multipliers as ISO for total dose, but does not limit to a specific orientation

$$A_{wt} = \sqrt{((1.4A)_{wx}^2 + (1.4A)_{wy}^2 + (A)_{wz}^2)}$$

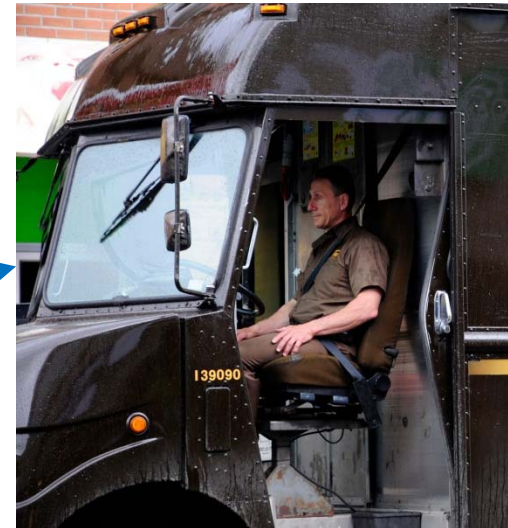
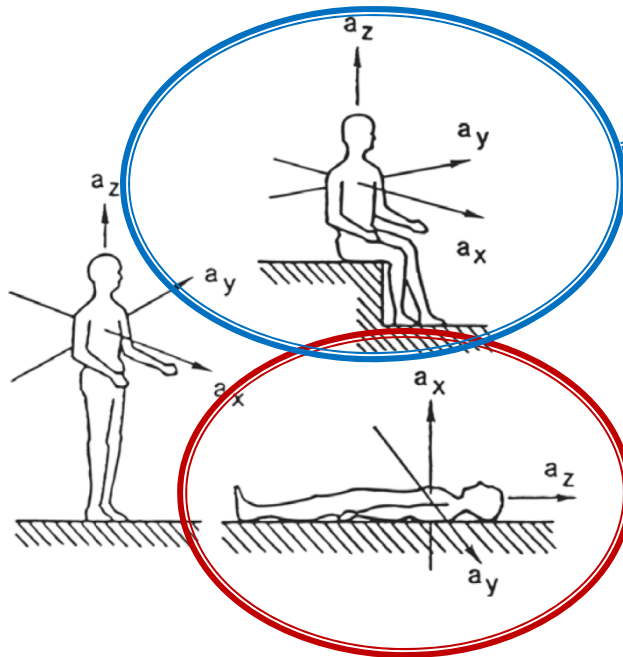
Applicable WBV Research



- Occupational health research focuses on upright orientation, e.g. drivers of heavy off-road equipment, helicopter pilots
 - Focus is more on neck and spinal pain and injuries,
 - Exposure tends toward impacts, lower frequencies
- Other research involves passengers and comfort
 - Perceptual thresholds when recumbent during transport, e.g. ambulances, sleeper berths on trains
 - Vehicle transportation of passengers in wheelchairs
- Prior aerospace research (1964)
 - Same body orientation, but focused on human tolerance to vibration
 - Performed prior to ISO frequency weighting scale established

Orientation & Applicability

Occupational Health Research



Passenger and Comfort Research



ISO 2631-1

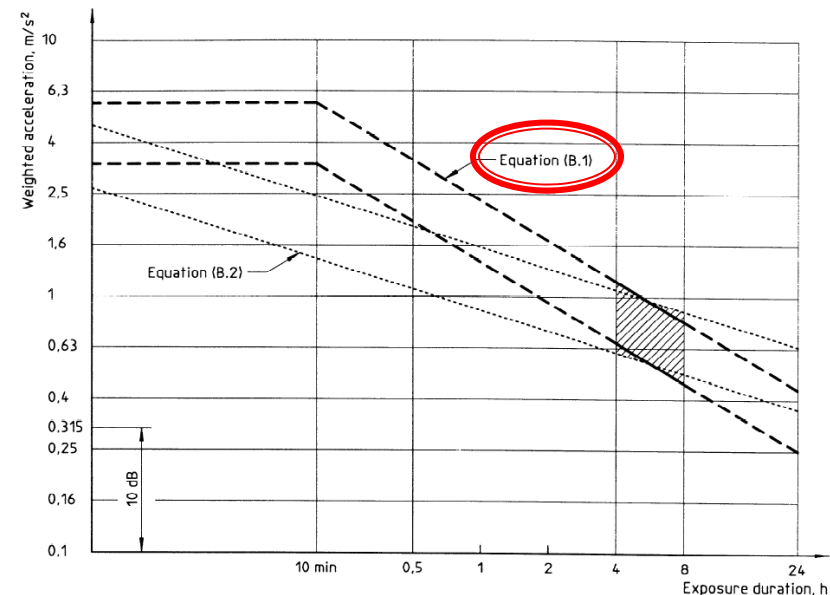
Health Guidance Caution Zone



- Annex B is the “Guide to the effects of vibration on health”, a synthesis of available biodynamic and epidemiological studies. It provides a Health Guidance Caution Zone:

- Zone Boundaries:

- Upper $A_{\text{was},8} = 0.85 \text{ m/s}^2$
(for 10 min = 5.88 m/s^2)
- Lower $A_{\text{was},8} = 0.45 \text{ m/s}^2$
(for 10 min = 3.18 m/s^2)



- Another reminder: “Most of the guidance in this annex is based upon data available from research on human response to z-axis vibration of seated persons. There is only limited experience in applying this part of ISO 2631 for X-, y-axes seating and for all axes of standing, reclining and recumbent positions.”

Crest Factor



- Crest Factor is used in the evaluation of the severity of vibration, particularly in relation to shocks.
 - ACGIH defines it as the ratio of peak to rms acceleration, measured in the same direction over a period of 1 minute for any orthogonal x, y, and z axes.
- ACGIH TLV – valid for vibration Crest Factor ≤ 6 . The TLV will tend to underestimate WBV effects when > 6 .
- ISO 2631-1 recommends additional evaluation when Crest Factor > 9 .

Requirements for HRVTB



- 8hr weighted average sum (WAS) exposure limit: time-weighted exposure dose for multiple exposures of varying level and/or duration that shall not be exceeded in a single work day.

$$A_{\text{was}(8)} \leq 0.566 \text{ m/s}^2$$

- *Rationale: Reduces the upper limit of the ISO 2631-1 Health Guidance Zone by 1/3 because the subject's orientation is reclining rather than upright. For comparison, the European Union WBV Daily Exposure Action Value = 0.5 m/s².*

Requirements for HRVTB



- Short Term Exposure Limit (STEL): frequency weighted rms acceleration as averaged over 10 minutes that shall not be exceeded at any time.

$$A_{\text{was(STEL)}} \leq 3.92 \text{ m/s}^2$$

- *Rationale: The upper limit of the Health Guidance Zone flat lines between 0-10 minutes at 5.88 m/s², so again reducing by 1/3. Note that exposures at this level for 10 minutes equate to the 8 hour exposure limit, $A_{\text{was}}(8) = 0.566 \text{ m/s}^2$.*

Requirements for HRVTB



- Crest Factor limit: ratio of maximum instantaneous peak acceleration to the frequency weighted rms acceleration over the duration of the exposure that shall not be exceeded at any time.

$$A_{\text{peak}} / A_w \leq 6$$

- *Rationale: Used the more conservative ratio between the ACGIHTLV cutoff (≤ 6) and ISO 2631-1 cutoff (≤ 9).*

Requirements for HRVTB



- Post-Test recovery period: no test runs shall be conducted after 2pm.
 - *Rationale: The Flight Surgeons had found that subjects in prior tests at another facility have shown negative residual effects up to 3 hours after completion of their last test run. Stopping test runs at 2pm gives test subjects sufficient time to recover before driving home. If more data are collected showing this outcome to be an outlier, this requirement may be relaxed to a shorter duration.*

Questions?



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